Information Theory for Mobile Ad-Hoc Networks (ITMANET)

A Fundamental Studies program in the Science of Interconnected Systems

7 March 2006

J Christopher Ramming / DARPA IPTO

STANDARD CAVEATS

- I have no authority to bind the government
- In the event of any discrepancies between material here and material on FedBizOps, the FedBizOps material takes precedence
- Anything and everything discussed here is subject to change – nothing is set in stone
- ITMANET is a work in progress

We are here to *refine* a program idea. Use your presentation time to that end.

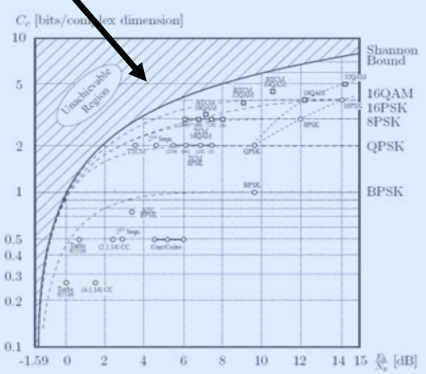
08:00am	**09:00am**	**Registration**	
08:45am	09:00am	Welcome and Introductions	Mr. J. Christopher Ramming / DARPA-IPTO
09:00am	09:45am	Overview: ITMANET Program Concept	Mr. J. Christopher Ramming / DARPA-IPTO
09:45am	10:15am	Army Perspective on MANETs (invitational briefing)	Dr. Ananthram Swami / Army Research Laboratory
10:15am	**12:00pm**	**RFI Submitter Presentations**	
10:15am	10:25am	Mobile Ad-Hoc Networks: Information Theory as a Design	Prof. Sergio Verdu/ Princeton University
10:25am	10:35am	A Theoretically-Motivated Network Stack	Dr. Karen Haigh / BBN Technologies
10:35am	10:45am	ITMANETs: Realism and Tractability	Dr. Gerard Foschini / Bell Labs
10:45am	**11:00am**	**BREAK**	
11:00am	11:10am	An Analytical Model for Evaluating Usable Throughput Capacity in Ad- Hoc Wireless Networks	Mr. Albert Futernik / ITT Aerospace
11:10am	11:20am	Developing a Layered Network information Theory: A Cross-Disciplinary Approach	Dr. Jeffrey Andrews / University of Texas at Austin
11:20am	11:30am	Limits of Connectivity in Mobile Ad Hoc Networks (MANETs)	Prof. Dennis Goeckel / University of Massachusetts
11:30am	12:00pm	Real world experience with MANETs (invitational briefing)	Mr. Tim Krout / Cengen
12:00pm	**1:00pm**	**LUNCH**	
01:00pm	01:30pm	Q & A Session	ALL
01:30pm	**3:45pm**	**RFI Submitter Presentations**	
01:30pm	01:40pm	How to Circumvent the Scalability Curse	Prof. Stuart Milner, Prof. Chris Davis, Prof. Zugmunt Haas / University of Maryland
01:40pm	01:50pm	Prospects for an Information Theory of Mobile Ad Hoc Networks	Prof. Gregory Pottie / UCLA
01:50pm	02:00pm	Information Theory for the Radios and Applications of Tomorrow	Prof. Anant Sahai / UC Berkeley
02:00pm	02:10pm	(Information Theory for Mobile Ad-hoc Networks)	Dr. Christian Peel / Brigham Young University
02:10pm	02:20pm	Importance of Realistic Mobility and Propagation for Capacity Assessment	Dr. Stephan Bohacek / University of Delaware
02:20pm	02:30pm	Information Theory for Mobile Ad Hoc Wireless Networks	Prof. P. R. Kumar / University of Illinois, Urbana-Champaign
02:30pm	02:40pm	Entropy Measures of Routing; Towards a First Law of MANET Infodynamics	Dr. Alhussein Abouzeid / Rensselaer Polytechnic Institute
02:40pm	02:50pm	Dimensioning MANET: A Real-Time Distributed Communication Approach	Prof. John Baras / University of Maryland
02:50pm	03:00pm	Information Theory Should Underpin Autonomous Networking	Mr. Albert L. "Larry" Raithel / QinetiQ Inc.
03:00pm	03:10pm	Theoretical Bounds for Capacity Ad-hoc of Mobile ieNetworks (MANETs)	Prof. Dharma Agrawal / University of Cincinnati
03:10pm	03:20pm	Fundamental Capacity Limits and Optimized Node Cooperation in MANETs	Prof. Andrea Goldsmith / Stanford
03:20pm	03:30pm	(Position Paper for the ITMANET RFI)	Prof. Anthony Ephremides / University of Maryland
03:30pm	03:40pm	MANET Capacity: Questions and Approaches	Dr. Joseph Cleveland / Samsung Telecommunications
03:40pm	03:50pm	Connectivity in Mobile Networks: A Dynamic Percolation Perspective	Dr. Yuliy Baryshnikov / Bell Labs
03:50pm	04:00pm	Capacity and Implementation: A Position Statement for ITMANET RFI	Dr. Uf Tureli, Dr. Didem Kivanc-Tureli / Stevens Institute of Technology
04:00pm	**04:15pm**	**BREAK**	
04:15pm	06:00pm	Open Discussions	ALL

A useful grand challenge in information theory

FACTORS AFFECTING MANET CAPACITY

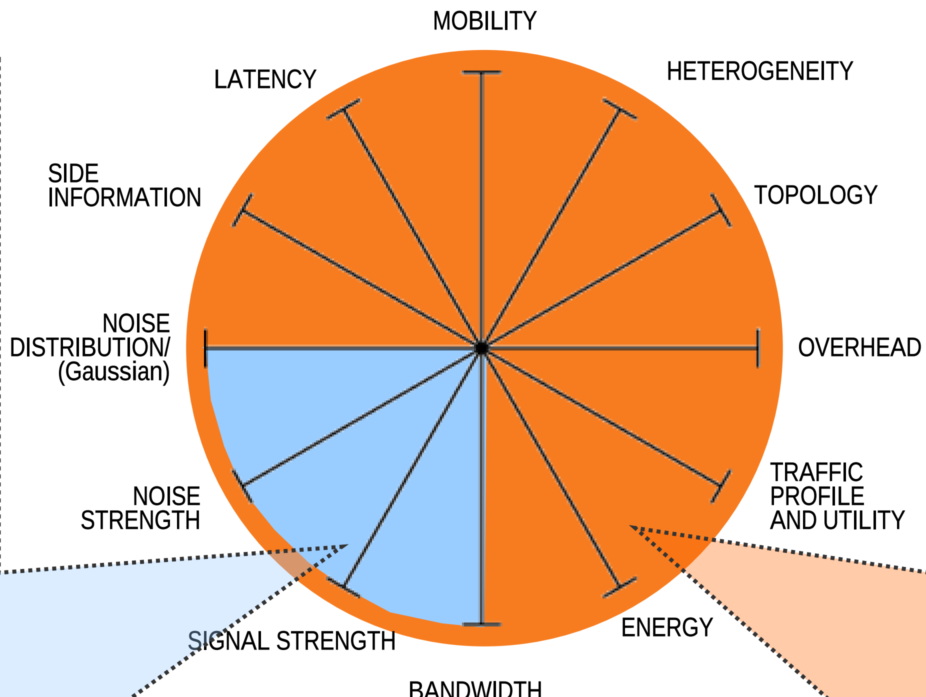
Point-to-point communications:

For AWGN channels, an upper bound on capacity is known



This knowledge is represented by the AWGN channel capacity limit formula:

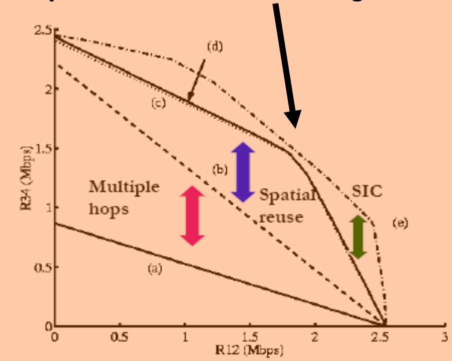
$C = W \log_2 (1 + S/N)$ **[bits/second]**



- Dimensions considered in Shannon formulation
- Dimensions considered in a future "unified theory of MANET Capacity"

Wireless "network" communications:

For wireless networks, an upper capacity bound is not known <u>except</u> when assuming specific current technologies



UNSOLVED Grand Challenge: Capacity Limits of MANETs

$C = ????????$

Objective: A new kind of information theory powerful enough to describe MANET capacity limits and tradeoffs

Military Utility: DOD Network Design, Deployment

Key DOD Uses of MANET Information Theory:

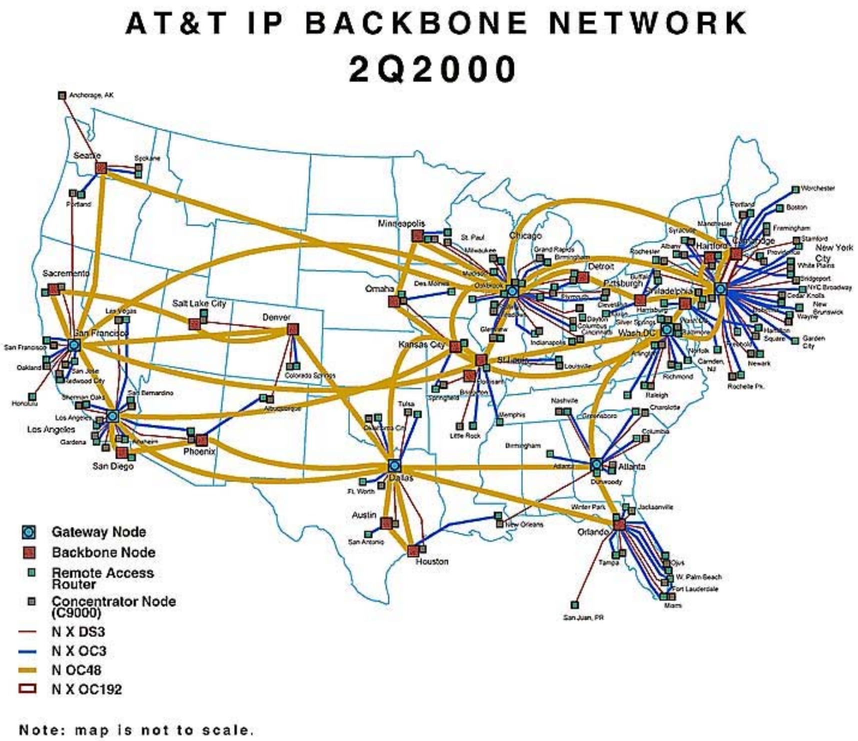
- **Doctrine**: what conops are possible given upper bounds on MANET capacity?
- **GIG acquisition strategy**: how good are present solutions? Which component investments are going to have the biggest impact?
- **Network planning and design**: determine tradeoffs concerning deployment options
- **Protocol design**: better protocols
- **Modeling and simulation**: more accurate models
- **Training**: accurate constructive and virtual extensions to wargames

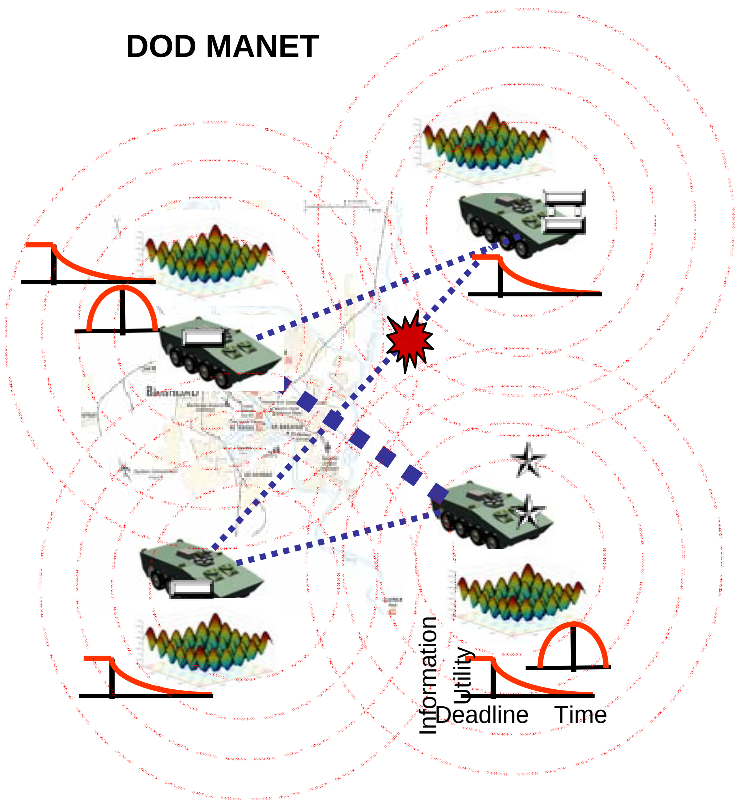
- Architecture
- Transmission strategy
  - Use of long distance transmissions vs short distance transmissions, media access approach, successive interference cancellation
- Topology
  - Discovery of specific topologies that scale
- Heterogeneity
  - Impact of infrastructure nodes, small worlds topologies,
- Capacity/latency/delay/energy/mobility
  - Tuning the network to the needs of the application
- Security
  - Encryption, network coding, VPN overlays
- Protocol parameters

- Medium-term DARPA need: theoretical foundations to bring DTN, CN, WNAN, ACERT, MNM, DCAMANET, and CBMANET into alignment

Lack of better theory hampers DOD acquisition strategy

Why MANET capacity limits are not obvious



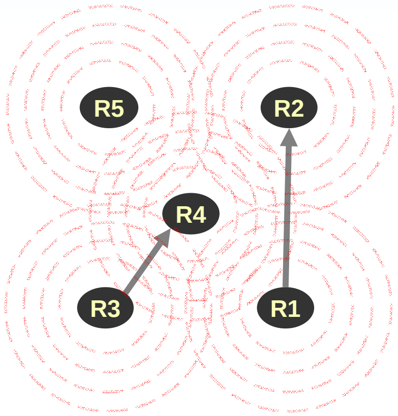


Wired Networks: network capacity is merely the sum of the link capacities

MANETs: capacity depends intricately on interference, mobility, delay tolerance, and electromagnetic transmission phenomena

Wireless “networks” comprise tightly coupled, interacting phenomena

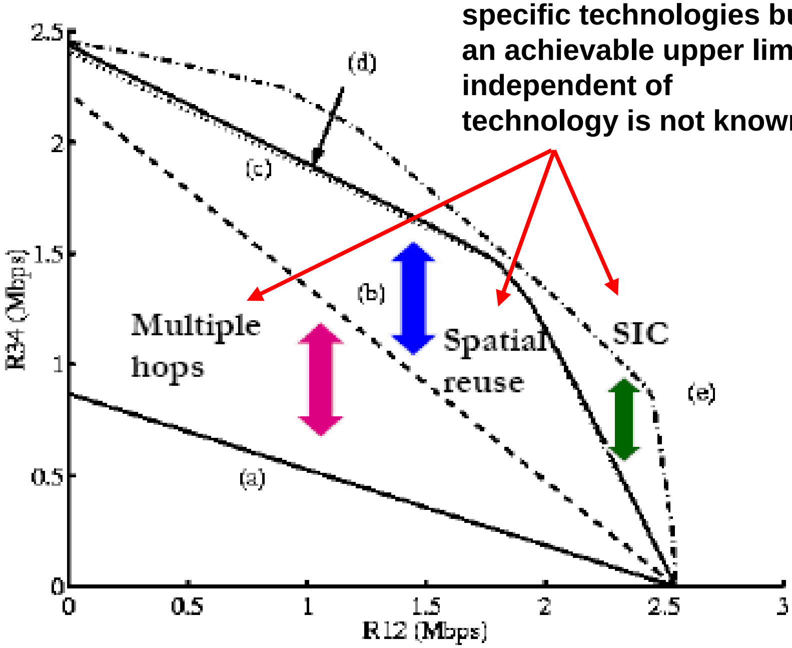
Limitations of present practice



A simple MANET deployment with interfering nodes

Capacity tradeoffs between R12 and R34 in the presence of different transmission protocols (multihop routing, spatial reuse, successive interference cancellation).

Capacity increases with increasingly powerful specific technologies but an achievable upper limit independent of technology is not known



For wireless networks, an upper capacity bound is not known <u>except</u> when assuming specific current technologies

Costs (energy, latency, overhead, security) are often not specifically addressed.

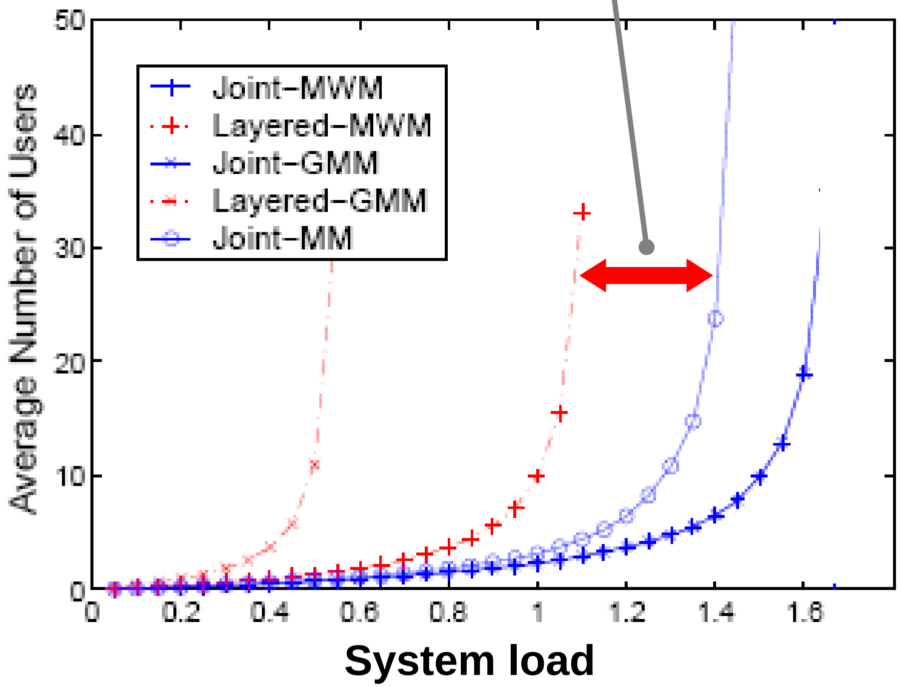
Results are often in the limits of large packet size, large network size, large number of frames, and other extremes

Source: Capacity Regions for Wireless Ad Hoc Networks, Toumpis and Goldsmith 2003

The Shannon capacity region of a MANET remains an open problem

Layered theory: a root cause of non-progress?

FIGURE: Red arrow shows that cross-layer scheduling algorithms (blue) outperform layered algorithms.



Note that MWM scheme more complex but superior to MM, yet layered MWM is inferior to cross-layer MM (red arrow).

MM = Maximal Matching scheduling algorithm (a simple scheme)

MWM = Maximal Weighted Matching (a better but more complex scheme than MM)

Rate limiting based on a "layered decomposition" conservatively estimates capacity and then solves for a transmission schedule.

In contrast, joint optimization substantially outperforms layered theories.

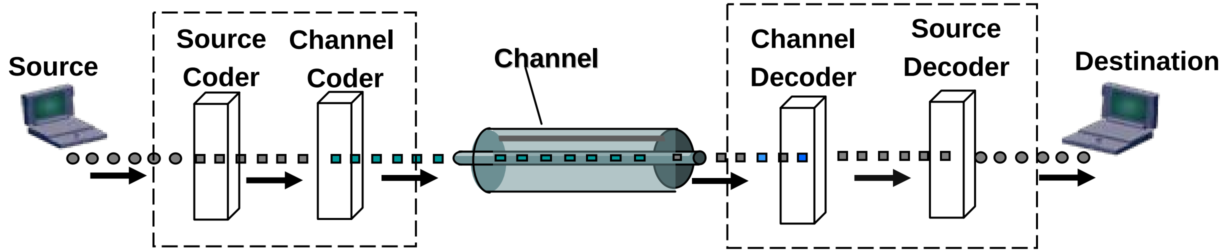
Source: Impact of Imperfect Scheduling on Cross-Layer Rate Control in Wireless Networks (Lin and Shroff 2005)

"Delayered theory" is one path ahead

On the other hand, layering can be useful

Shannon Source-Channel Separation Theorem

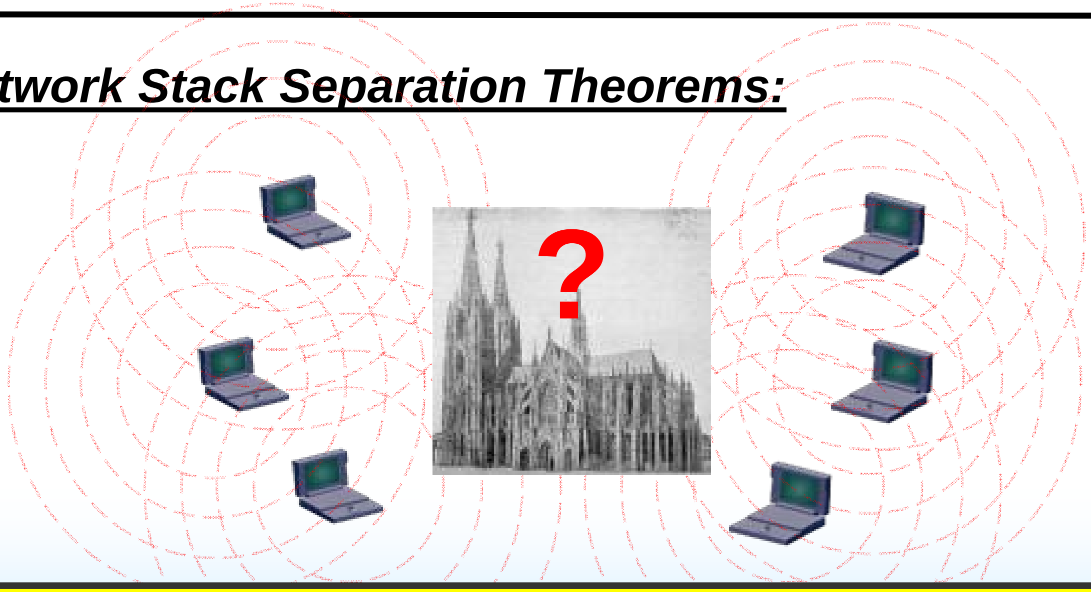
- Associate compression with the source
- Associate error coding with the channel



Implications

- **Reliable transmission can be accomplished by separate source and channel coding**
- **Source coding/decoding is independent of the channel**
- **There is nothing to be gained from considering joint source/error coding**

Network Stack Separation Theorems:



Do new separation principles exist to guide MANET architecture?

Useful, theoretically motivated separations may also emerge from ITMANET

Can mysterious experimental results unblock theory?

FIGURE BELOW: How network coding can transmit multiple packets per hop

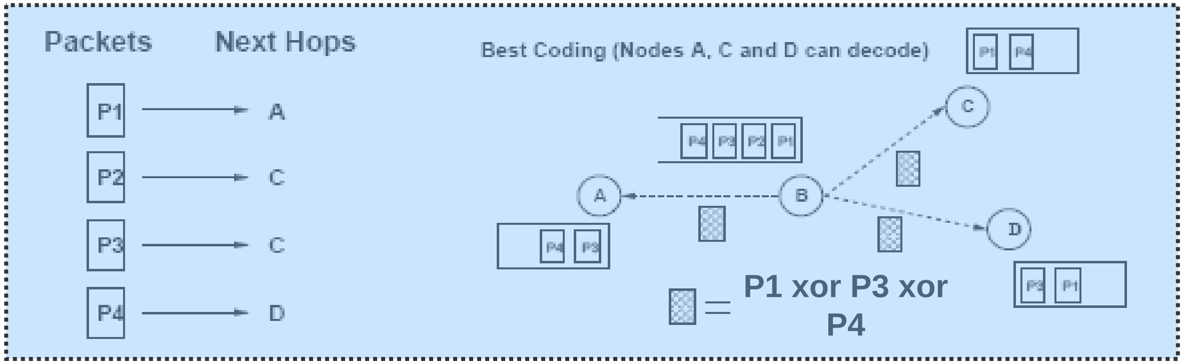
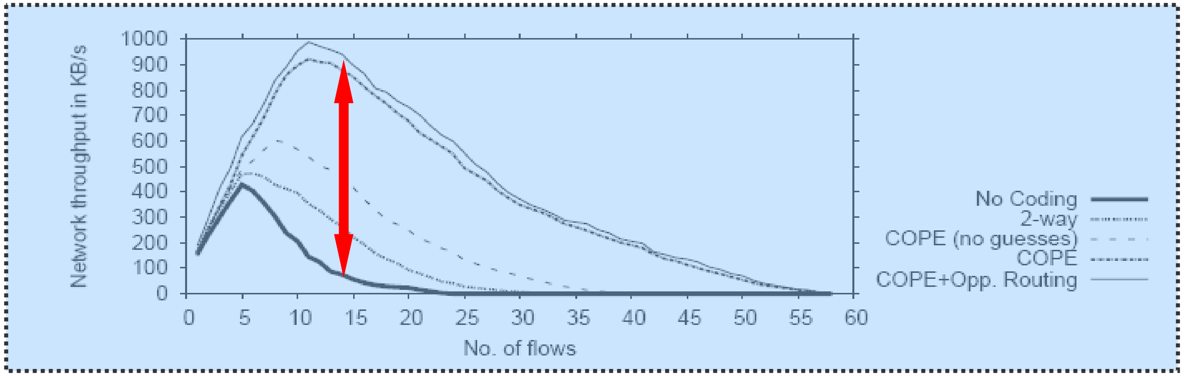


FIGURE BELOW: Red arrow shows huge improvement relative to no coding that is smaller when 802.11 is not used in "promiscuous" mode

What accounts for this mysterious improvement?



Network coding benefits to unicast are not understood by theory, which primarily highlights benefits to multicast. Yet experimental results show orders of magnitude benefit in certain cases.

One possible explanation is that network coding can overcome the limitations of weak multiple access mechanisms (e.g. CSMA/CA).

Source: The Importance of Being Opportunistic: Practical Network Coding for Wireless Environments, Katti et al 2005

Speculation: any layered theory that separates the physical and media access issues may be inherently flawed given enablers such as network coding

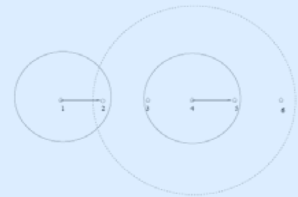
State of the Art in MANET Capacity Analysis

2000 2001 2002 2003 2004 2005 2006 2007 2008

***A scare for FCS*.** Gupta & Kumar show that the capacity of MANETs scales as n/sqrt(n). That is, the capacity of individual users goes to 0 as the network gets large.

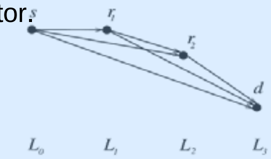
Limitations: random placement of nodes; random pointwise connections; no mobility; result is in the limit of a large number of nodes rather than specific use cases

Topology and traffic patterns matter. Li *et al* show that certain traffic patterns and certain topologies scale, e.g. a long chain carefully spaced nodes has capacity ¼ sending rate independent of network size



Limitations: no mobility; specific use cases considered; no general theory derived

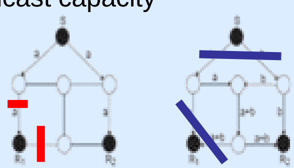
Multiuser coding matters. Gupta & Kumar show that successive interference cancellation and multiuser coding schemes increase network capacity per user to a constant factor.



Limitations: no mobility, random pointwise connections; random topology, no network coding; algorithm scalability

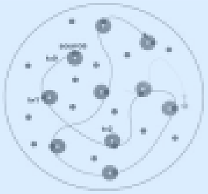
Grand Challenge in MANET Information Theory: Precise characterization of MANET capacity with a unified accounting for mobility, uni/ multi/ omnicast, latency, topology, energy, and multiuser issues

Network coding matters. Ahlswede *et al* show seminal result that network coding strictly increases multicast capacity



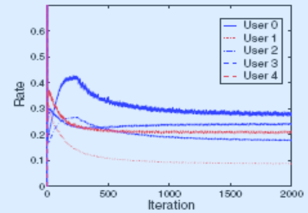
Limitations: added computational complexity

Mobility and latency matter. Grossglauser & Tse show that mobility raises the network capacity to a constant factor independent of size.



Limitations: memory requirements and latency limits are both unbounded

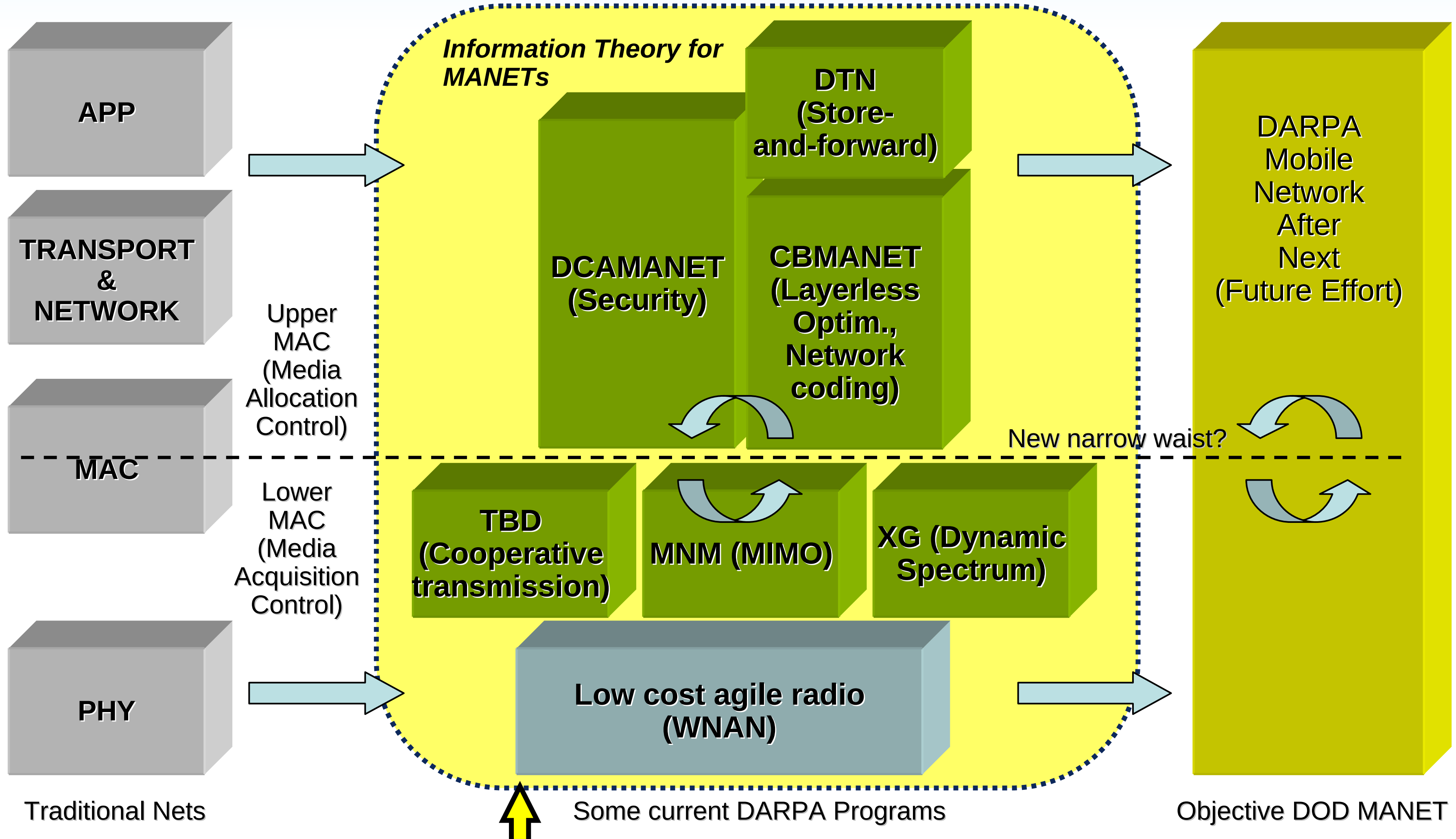
Cross-layering matters. Lin & Shroff prove that a cross-layer approach is strictly superior to a layered approach.



Limitations: optimal scheduling is complex and does not necessarily have a polynomial-time solution

Current investigations are not yet tackling the full problem

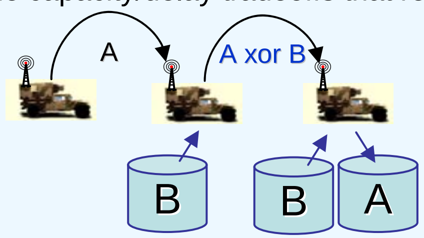
Relationship to other DARPA programs



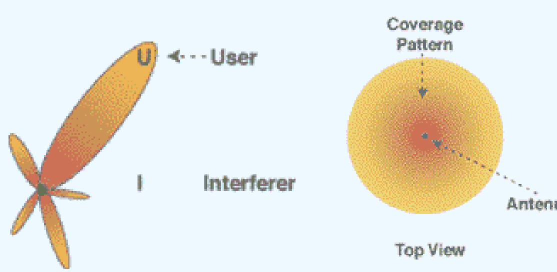
Theoretical foundations for a grand unification of DARPA program results

Questions that need answers in the 2-3 year horizon

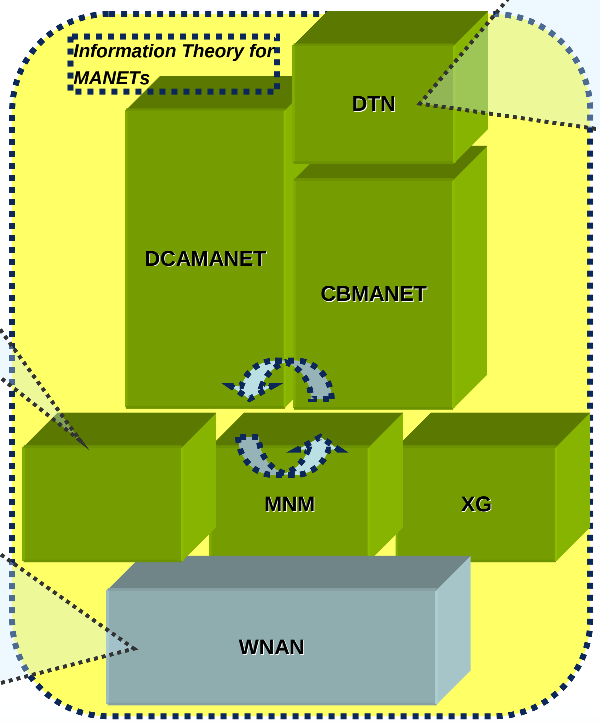
Insight: network coding and disruption-tolerant store-and-forward protocols both exploit router memory. Should DTN protocols be incorporated into lower-level network coding protocols, and how? What are the capacity/delay tradeoffs that result?



Insight: probabilistically defined network coding hyperarcs provide a protocol mechanism for exploiting smart antennas that can adaptively beamform, broadcast, cancel interference, and perform MIMO transmission. What is the best way to exploit these degrees of freedom in a network?

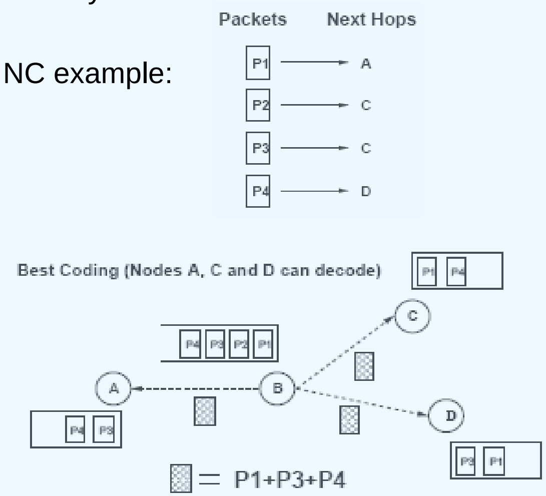


Core CBMANET technology (network coding, layerless architecture, distributed optimization) is well-positioned to incorporate other program results.

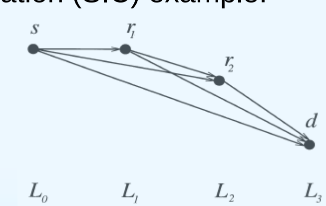


Insight: network coding and certain cooperative transmission schemes (e.g. successive interference cancellation) both involve prepositioning information for subsequent exploitation. What is the precise relationship between these concepts, and can they be combined usefully?

NC example:



2-level successive interference cancellation (SIC) example:



Even if the full problem is not solved, intermediate byproducts have value

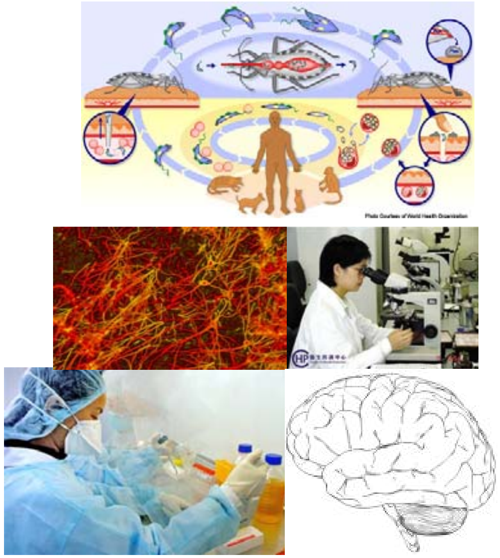
DOD RELEVANCE:
Toward a larger "science of interconnected systems"

The security of the nation rests on better networks, which requires better theoretical foundations

- Design and deployment principles
- Relationships and interactions of multi-scale networks
- Relationship between the statics and dynamics of networks
- How to predict performance and resilience from analysis of multi-scale network architectures
- How to predict and control critical network "tipping points"

DOD Data Networks

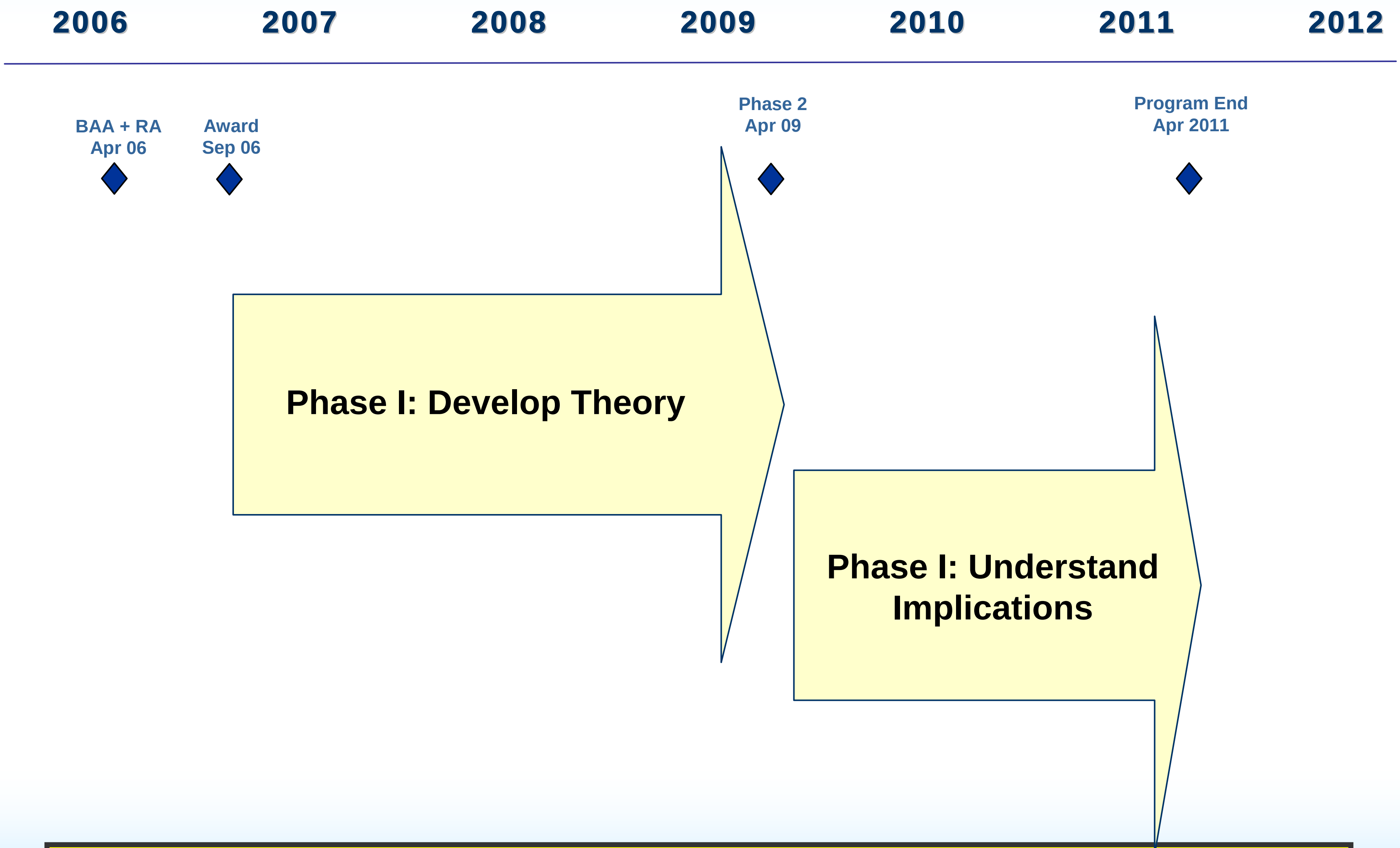
Biological / Epidemiological / Social Networks



Logistical / Supply Chain / Power Networks

A byproduct of solving the MANET capacity problem challenge will be mathematical tools that help in other networking domains

Tentative Program Schedule



Two phases: first develop theory, then understand the practical implications

Potential Program “Metrics”

- Seeking major theoretical breakthroughs in the Information Theory of MANETs
- Using exceptional research teams
- Resolving the “unconsummated union” between information theory and networking
- Visibility across multidisciplinary communities
- Potential for intermediate-term DOD impact

Unlikely to have typical go/no-go metrics, but progress will be evaluated periodically

Potential intermediate questions and deliverables

In the proposal itself, we should see the following answers:

- (Q) What definition(s) of capacity do you intend to understand?
- (Q) What problem formulation are you tackling, and how should your success be evaluated at the end of the program?
- (Q) Which problem dimensions will your formulation address?
- (Q) What balance between completeness of theory and utility of theory do you intend to strike? On what grounds is the proposed (objective) theory likely to have implications for DOD practice?
- (Q) What is the enabling insight that will allow the proposer to make progress when the problem has proved over-challenging heretofore?
- (Q) What subquestions need to be answered to achieve the result? What timeline is proposed for investigating those subquestions?
- (Q) Apart from capacity, what is the most important set of tractable information-theoretic questions or corollaries that will be addressed within the timespan of the proposal? What subquestions and timeline for answering those subquestions is proposed?
- (Q) To what extent do results from other fields (e.g. physics) seem to be important and how will those results be explored in a multidisciplinary research plan?

The questions posed in the BAA and by the proposers will provide insight into proposers' depth of understanding and constructive plan

End of Phase 1 (30 months): Theory

- (D) Report on the most comprehensive theory achieved by the proposer at the end of Phase 1
- (Q) To what extent is the theory valid for specific cases and/or in the limit of problem variables?
- (Q) What is the theoretical basis of a relationship between emerging technologies such as network coding, successive interference cancellation, multihop routing, MIMO, beamforming, encryption?
- (Q) What aspects of networking will be affected by the results to date (information assurance, performance, specific networking protocols) and what is the Phase 2 plan for exploring those implications?
- (Q) What technologies are best positioned to achieve fuller network capacity and how (for example, see the questions related to network coding on slide 11 of this briefing)
- (Q) For present networks, what are the implications for best practices in network planning, design, and deployment? Are there short-term implications of the results that can be exploited?
- (D) Report on relationship between information theory, networking, and potentially other fields such as physics
- (D) Report on extent of refereed papers and citations resulting from this effort as an indicator of impact

End of Phase 2 (24 months): Implications

- (D) Implemented models of network performance enabled by the new insights
- (D) Analysis of the "headroom" available for further progress relative to current protocols
- (D) Invention of new wireless networking "technologies" that exploit hitherto-unimagined areas of the theoretical capacity limits
- (D) Implications for novel protocol designs, and prototypes of those novel prototypes if possible
- (D) Report on DOD impact of the results, plus recommendations for the future

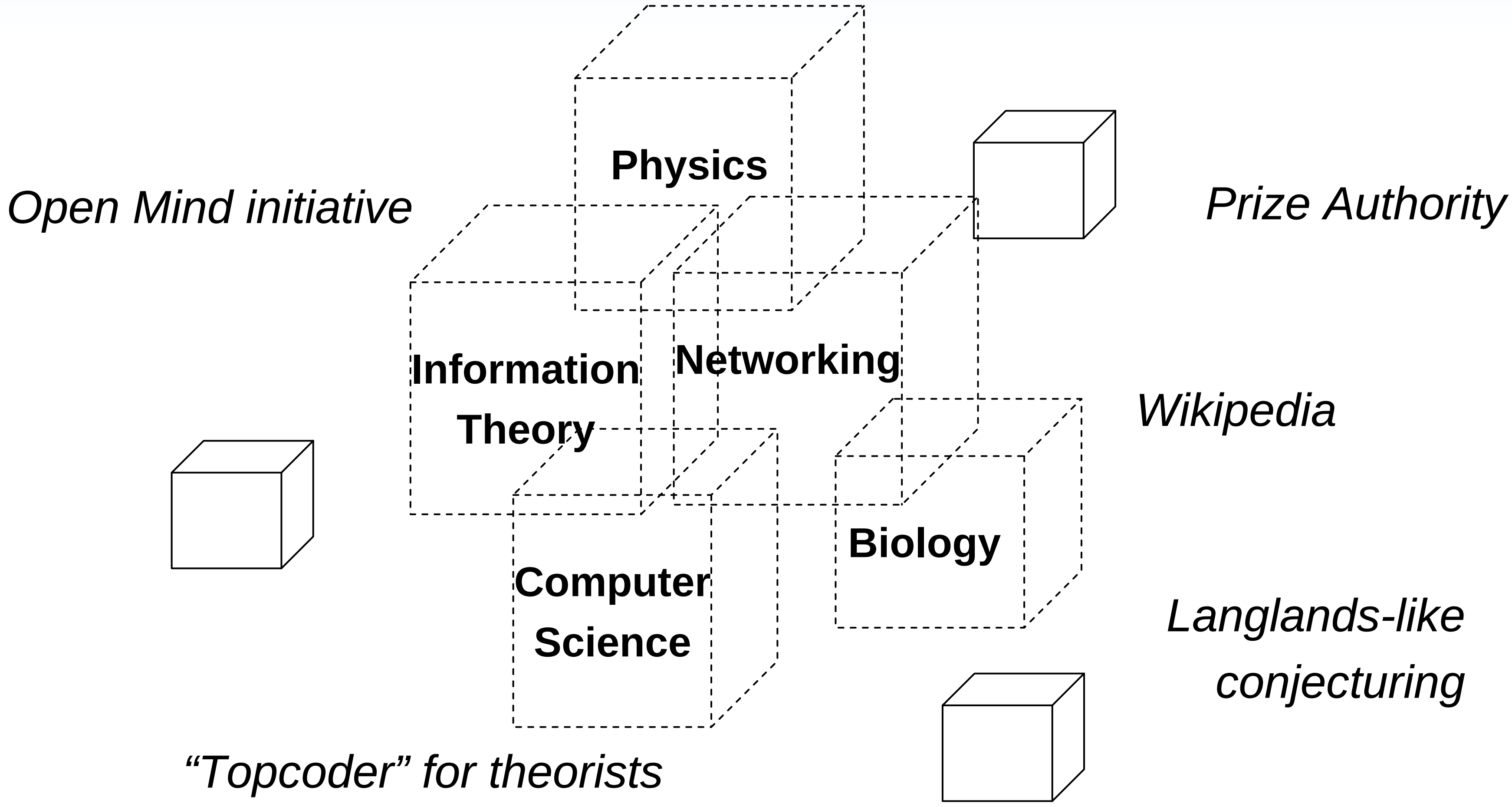
We will rely in part on the proposals to describe what is achievable

Potential Solicitation Evaluation Criteria

- Problem Understanding and Innovative Technical Approach
  - Assessed in part by answers to the RA/BAA questions
- Qualifications and time commitments of the key individuals
- Constructive Plan / Research Agenda Realism
- Contribution to DARPA mission
- Cost realism

Hiring the right people is as important as funding a good constructive plan

Are there any novel proposal elements to consider?



Imagine how Oppenheimer might have approached an unclassified challenge in the Internet era

Anticipated Acquisition Strategy: Two Solicitations

Open solicitation via BAA (Broad Agency Announcement)

- Full & open competition
- Foreign participation restrictions not yet decided

Targeted solicitation via RA (Research Announcement)

- Restricted to grant institutions
- Special rules limiting participation to “Young Investigators”
- “Young Investigator” definition TBD, but tentatively tenure-track individuals having received their degree no more than 4 years prior to the date of the anticipated solicitation

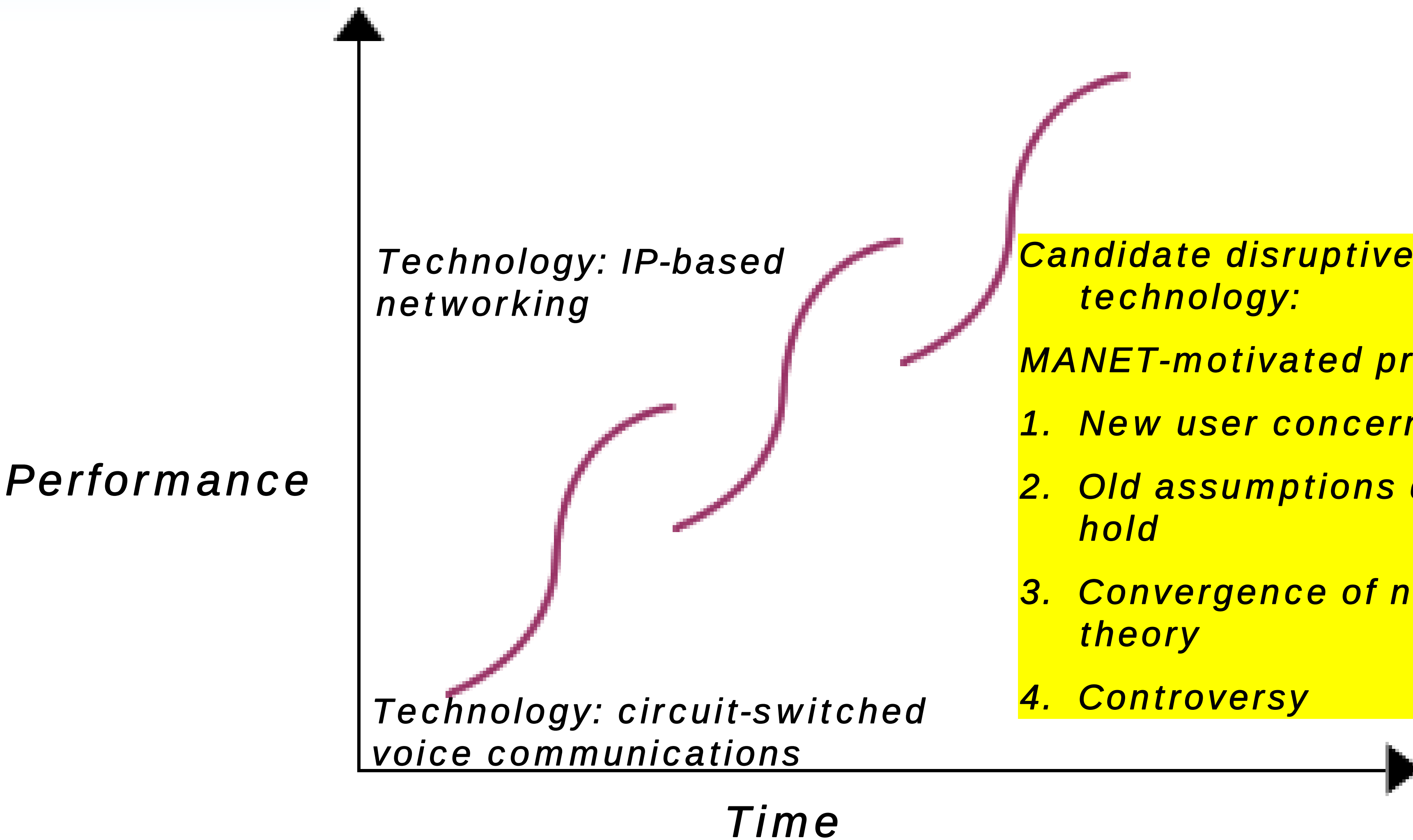
Anticipated funding of $13.5M over 4.5-5 years

SUMMARY: Information Theory for MANETs Program Concept

- **What?**
  - MANET capacity understanding as a challenge problem with many side benefits
- **Why?**
  - Huge DOD network investment will benefit from better theoretical underpinnings
- **What & How?**
  - Long-term fundamental research on the information theory of MANETs
- **Why now?**
  - Many enablers of progress have been identified
- **Why DARPA?**
  - DARPA has a tradition of coordinating focused research efforts, as well as the practical grounding to make those efforts useful

Useful progress is imminent but needs focus

Where will the next networking paradigm shift come from?



Candidate disruptive technology:

MANET-motivated protocols

1. New user concerns
2. Old assumptions do not hold
3. Convergence of novel theory
4. Controversy

The most challenging networking contexts will generate disruptive technology. Theory will point the way ahead.

Questions?

- Please write questions and afternoon debate topics on the 3x5 cards and I will try to answer them after lunch
- Think of something later? Send it to itmanet-rfi@darpa.mil with a cc to james.ramming@darpa.mil

Thank you for your participation